Results from HARP

Malcolm Ellis
On behalf of the HARP collaboration
DPF Meeting
Riverside, August 2004
The HAdRon Production Experiment

124 physicists

24 institutes
Physics Goals

• Input for precise calculation of atmospheric neutrino flux

• Input for prediction of neutrino fluxes for the MiniBooNE and K2K experiments

• Pion/kaon yield for the design of the proton driver of neutrino factories and SPL-based super-beams

• Input for Monte Carlo generators (GEANT4, e.g. for LHC, space applications)

Systematic study of HAdRon Production:
Beam energy: 2-15 GeV
Target: from hydrogen to lead.
**Data Taking Summary**

HARP took data at the CERN PS T9 beam-line in 2001-2002

Total: 420 M events, ~300 settings

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### ν EXP:

**K2K: Al**

- 5%
- 100%
- Replica

**MiniBoone: Be**

- 5%
- 100%
- Replica

**LSND: H₂O**

- 10%
- 100%
- Replica

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<tr>
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<td>Replica</td>
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<td>+12.9 GeV/c</td>
<td>+8.9 GeV/c</td>
<td>+1.5 GeV/c</td>
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TPC – Large Angle

• Full track reconstruction available

• Calibration campaign in 2003:
  – Calibration with sources (\(^{55}\)Fe, \(^{83}\)Kr)
  – Calibration with cosmic rays.

• Systematic study of corrections:
  – Basic calibrations revisited (time, charge, position)
  – Cross-talk correction
  – Distortion corrections
TPC Cross talk

Cross-talk model
- Capacitive couplings
- Preamplifier transfer functions

Cross-talk measurements
- Individual pulse injection in all pads
- 50% of pads affected by x-talk
- X-talk only relates to neighbouring pads

Full simulation exists

Oscilloscope DAQ

Residuals
- RMS ~ 3 mm

Introduced in MC

Capacitive couplings

# Daughters
Momentum & dE/dx

Compare single arm with full track

\[ \Delta p_t = \text{abs}(\rho_1 + \rho_2) \]

\[ p_t = \sqrt{2(\rho_{\text{tot}})} \]

\[ \rho \propto \text{charge } 1/p_t \]

\[ A \times \left( \frac{1}{\beta^2} \right) \]

protons

Muons and pions

\[ \Delta p_t/\rho_t = (0.56 \pm 0.04) \rho_t + (0.08 \pm 0.014) \]

\[ \chi^2 = 0.62 \]
Elastic Scattering

- Red: using \( \frac{dE}{dx} \) for PID
- Blue: Simple selection
  - Only 1 pos. track in the TPC coming from the target
- Red: Additional cut on \( \frac{dE}{dx} \) in TPC (select proton)

missing mass for \( p \ p \rightarrow p \ p \) and \( \pi p \rightarrow \pi p \)
- Select \( p \) and \( \pi \) in the beam by ToF

\[ p \ p \rightarrow p \ p \]
\[ \pi \ p \rightarrow \pi \ p \]
Forward Analysis

- $p_\pi > 1\text{GeV/c}$
- $\theta_\pi < 250\text{ mrad}$
- Main tracking detector: NOMAD drift chambers
- Forward PID detectors
Beam Instrumentation

Beam composition and direction

MWPCs

Beam Cherenkov
- K-π separation at high energy

MiniBooNE target

Beam Tof
- k/π/p separation at low
- T0

T9 beam
CKOV-A
TOF-A
CKOV-B
TOF-B
MWPCs

21.4 m

12.9 GeV

3 GeV

K
π

π

k
p
d
NOMAD Drift Chambers

Cosmic rays

Alignment

Iter 1

Iter 2

Resolution

Iter 10

\[ \sigma = 340 \mu m \]

Hit reconstruction efficiency

\~ 80 \%

\begin{itemize}
  \item 95 \% in NOMAD
  \item Harp: Not flammable gas (safety regulations)
\end{itemize}

Module eff

Lateral modules

Courtesy of NOMAD
$m^2 = p^2 \cdot \left( \left( \frac{t_w - t_0}{L} \right)^2 - 1 \right)$

- Tof ~160 ps
- $7\sigma \pi/p$ @ 3 GeV
- Beam ~70 ps
$\pi/p$ using Cherenkov

$\pi/p \ p > 3$ GeV

$\pi/k \ 3 < P < 9$ GeV

$N_{phe} \propto N_0 \left(1 - \frac{1}{n^2} \left(1 + \left(m/p\right)^2\right)\right)$
e/π using calorimeters

- “Spaghetti” type
- Courtesy of the CHORUS experiment
- 2 planes (EM1, EM2)

Resolution

\[ \frac{\sigma_E}{E} = \frac{23\%}{\sqrt{E(\text{GeV})}} \]

\[ \text{observed resolution} \]

\[ \text{Energy, EM1/EM2} \]

3 GeV

electrons

pions
NDC Tracking Efficiency

- Multi-track events (hit efficiency, hit density, pattern recognition) → tracks type 1 (3-d segment in NDC1) “migrate” to type 2 tracks (2-d segment in NDC1) and type 3 tracks (hits in NDC1)

- Tracks type 2 & 3 + vertex constrain → measure \((p, \theta, q)\).
  - Size of migration → hadronic model dependent
  - Total efficiency → hadronic model independent
Cross section

\[ \sigma_{ij}^\pi = F_{\text{norm}} \cdot M_{ij}^{kl} \cdot \frac{1}{\epsilon^{\pi}_{kl}} \cdot \left( N_{kl}^\pi - N_{kl}^{bkg} \right) \]

\[ \sigma_i^\pi = \frac{1}{\epsilon_i^{\text{acc}}} \cdot \frac{1}{\epsilon_i^{\text{track}}} \sum_{t=1}^{3} \left[ M_{ij}^{(t)} \frac{1}{\epsilon_j^{(t)-\pi}} \eta_j^{(t)-\pi} \cdot N_j^{(t)-\pi} \right] \]
Cross section revisited

\[ \sigma_{ij}^\pi = \frac{1}{\varepsilon_{acc}^i} \frac{1}{\varepsilon_{track}^i} \sum_{t=1}^3 \left[ M_{ij}^{(t)} \frac{1}{\varepsilon_{j}^{(t)-\pi}} \eta_j^{(t)-\pi} \cdot N_j^{(t)-\pi} \right] \]

- track types
- Tracking efficiency
- Pion purity
- Measured pion yield
- Runs on bins of \((p, \theta)\)
- Acceptance
- Migration matrix
- Pion efficiency
Tracking efficiency

\[ \varepsilon_{i, \text{track}} = \frac{N_i^p}{N_i^{\text{acc}}} = \frac{N_i^{\text{down}}}{N_i^{\text{acc}}} \cdot \frac{N_i^p}{N_i^{\text{down}}} = \varepsilon_{i, \text{down}} \cdot \varepsilon_{i, \text{up-down}} \]
Module acceptance and efficiency

Acceptance of modules 3, 4 & 5 normalized to acceptance in module 2 as a function of $p$ and $\theta_x$ (MC)

Tracking efficiency of modules downstream the dipole as a function of $x_2$ and $\theta_{x2}$ (DATA)
Downstream tracking efficiency

\[ E_{\text{down}} \sim \text{cte}(p, \theta) = 98\% \]
Total tracking efficiency as a function of $p$ (left) and $\theta_x$ (right) computed using MC properly scaled by data.
PID probabilities

\[ P(p, \lambda | \pi) \quad P(p, \overline{N}_{phe} | \pi) \quad P(p, E_1, E_2 | \pi) \]

tof

\( \lambda = m^2/p^2 \)

cherenkov

\( N_{phe} \)

ecal

\( E_1 \) vs \( E_2 \)

electrons

pions
Pion correction factor

- The yield of each track type must be corrected by pion efficiency & purity
- Compute using beam particles (clean particle selection from beam detectors)

\[
\varepsilon_i^{\pi-i} = \frac{N_i^{\pi-\text{true-obs}}}{N_i^{\pi-\text{true}}} = \frac{\text{tracked true pions identified as such}}{\text{tracked true pions}}
\]

\[
\eta_i^{\pi-i} = \frac{N_i^{\pi-\text{true-obs}}}{N_i^{\pi-\text{obs}}} = \frac{\text{tracked true pions identified as such}}{\text{tracked particles identified as pions}}
\]
K2K target – Pion yield

- Raw
- Efficiency
- PID
- Acceptance
Summary and Outlook

- HARP first results using the K2K replica target are now available.
- Measurement needed to improve the calculation of the far/near ratio in K2K will come soon.
- A similar analysis is proceeding on the MiniBooNE replica target (see talk by L.Coney).
- Further measurements of interest to the neutrino physics community will be provided by HARP in the near future...